Designing Sustainable Launch Systems

Flexibility, Lock-In and System Evolution

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NASA has recently made the decision to develop a heavy lift launch system with Shuttle-Derived components, but myriad questions remain about technical design and development strategy. The complexity of heavy lift launch systems and their interconnectedness to the rest of the exploration architecture ensures that near-term architectural design decisions will greatly affect long-term options for future space exploration. This paper uses Real Options valuation to compare two possible development plans for a heavy lift launch system. Taking into account cost profiles, capacity, and uncertainty in demand, various heavy lift vehicle strategies are presented and evaluated along plausible development paths. These strategies can be framed as Shuttle-Derived-Architectures with "options" to change capability in the face shifting demand and risk tolerance scenarios. Initial results suggest that life-cycle optimality is heavily dependant on schedule uncertainty, while less sensitive to lunar and mars mission architectures and initial mass in low earth orbit (IMLEO). Future work will involve more detailed analysis of switching options and switching costs, as well as a more comprehensive network model of switching decisions in order to compare more vehicle configurations.

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1.0 Introduction

A principle determinant of *comparative* sustainability from an economic perspective involves the pattern of spending associated with development and operations, under various demand scenarios. For example, in the early 1980's cost models demonstrated that the Space Shuttle was more affordable than expendable systems only at inordinately high levels of demand. While political pressures may have induced various groups to advocate for their demand-scenario of choice, the reality, as always, proved unpredictable. All scenarios are best-guesses, lying along a probability distribution which is itself difficult to ascertain.

Real Options Analysis provides a method to design systems that capitalize on, rather than suffer from these inevitable fluctuations in the operating environment. It provides a framework to quantify how system attributes that often decrease optimality in a fixed operating scenario may enhance *flexibility* and thus "life-cycle optimality" over time. The goal of the analysis is to quantify the benefits of designing systems that are more flexible and reactive in the face of uncertainty—and thus more sustainable for long-term endeavors like space exploration.[3]

This section describes a model of the forthcoming decision on Heavy Lift Launch that uses using "real-options thinking." The model presented here compares Shuttle-Derived Vehicles (SDV) to EELV-derived architectures (EELVD), under various demand scenarios, in order to answer the following critical question: *Which is more cost effective from a life-cycle perspective: SDV or EELVD with an option to expand?*

This question can be framed as an option on EELV vehicles. Shuttled derived vehicles provide 80+ metric-ton (mt) capability to LEO.[1] However, because preliminary results indicate that a vehicle considerably lower than the 80mt may be adequate for lunar missions, it is conceivable to design a smaller system based on EELV-derived components with the *option to expand for future Mars missions*. These options could take multiple forms, including launch-pad modifications or allowances for additional stages or booster-rockets. While SDV systems have the advantage of having much hardware already built, EELV systems could have the advantage of being smaller, cheaper to maintain, and more agile in the face of change.

2.0 Real Options Thinking in a Nutshell

A major goal of Real Options Analysis is the development of a clear, understandable measure of flexibility.[2] Real options valuation is based directly on the valuation of financial options. While it is not the purpose of this report to examine the details of Real Options Theory, the following information will be useful for understanding the model and analysis below.

An option, whether financial or real, is formally defined as "a right, but not an obligation, to take action now or in the future at a pre-determined price." [2] In finance this takes the form of a contractual agreement to buy or sell a stock at a pre-determined price (called the *strike-price*). The right to buy a stock is called a *call option*. The right to sell is called a *put option*.

[3] For a good primer on Real Options, see: de Neufville, Richard. "Architecting Systems Using Real Options." ESD Working Paper, May 2002. http://web.mit.edu/spacearchitects/Archive/Real%20Options%20Working%20Paper.pdf

Financial options also come in two varieties depending on when they can be exercised. *European Options* must be exercised on a pre-determined date. *American Options* can be exercised anytime before their expiration date. The majority of traded financial options, like real options, are American.

Similarly, a *Real Option* is as an element in the system (or on the system), which allows managers to take an action now or in the future at a pre-determined price. For example, designing EELVs so that they can accommodate varying numbers of booster rockets creates "the right, but not the obligation" to enhance lifting capability if the market demands. Booster rockets, and the design modifications to the main rocket needed to support them, can be defined as an *American Option in the ELLV system.*

Real options can be either *in* a system, or *on* a system. An option *in* a system is a technical construction that provides the ability to change or add something to the system. As noted, booster rockets are options in the EELV system. An option *on* a system entails the right to develop that entire system or program at a given time. For example, certain purchases might need to be made in order to keep the option to develop a Shuttle-Derived vehicle in the future. The actions taken to keep this possibility open can be framed as an option *on* the Shuttle Derived Program.

As all system designers know, options that make a system more flexible come at cost and degradations in system-performance. Real options analysis allows the classic question "how much is this flexibility worth?" to be reframed as: "How much is the Real Option worth?"

There are multiple methods, all more or less complicated, to modeling the value of real options. Suffice to note here that the value of an option stems from three basic features: 1. asymmetric risk 2. Uncertainty in demand 3. The value of information and the discretion of managers. Options have asymmetric because once purchased, they have an upside but practically no downside (other than potential loses in performance which remain fixed). Because the future is uncertain and new information arrives constantly, options give managers the discretion to alter system attributes more flexibly, so they can take advantage of this upside when needed. Valuing real options thus demands an understanding of the level of uncertainty in demand, and the financial and performance costs associate with the system.

In its simplest instantiation (and quite often, the most appropriate given error-levels in the data and the need for practicality), a decision tree approach can be used. This approach combines the probability that different paths might be taken with the economic concept of "expected cost," in order to compare the cost of different systems in different scenarios. This will be used for our model, and described in more depth below.

3.0 Elements of Life-Cycle Cost

The value of Real Options is dependant on both the level of uncertainty surrounding critical demand variables (the probability distribution of future demand), and the cost-profile of the systems being deployed. The life-cycle cost of a launch system, as with many other kinds of systems, can be partitioned into three main categories: Development Cost, Fixed Recurring Cost, and Variable Recurring Cost. Figure 1 illustrates the relationship between these costs.

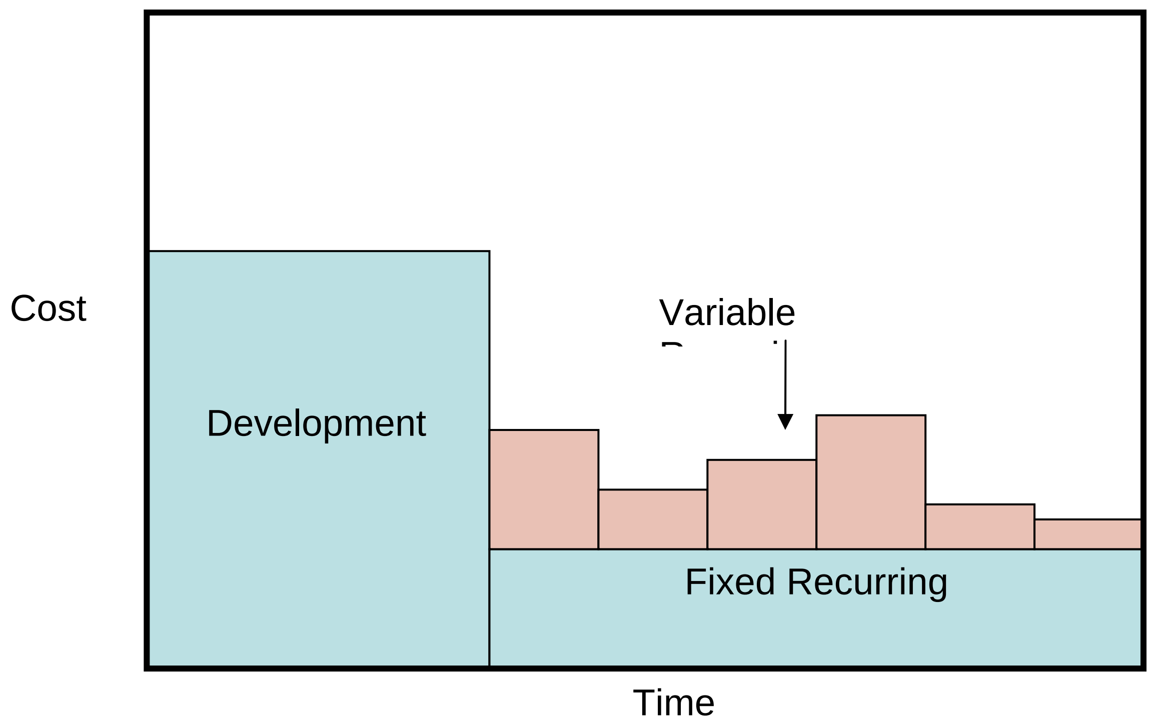

Figure 1: Elements of Launch Vehicle Life Cycle Cost.

Development Cost includes Design, Construction, Testing, and Evaluation of the launch system before it is deployed. It includes all elements of the program prior to operations.

Fixed Recurring Cost includes the cost of maintaining the launch system, regardless of whether there are any launches in a given year. It includes basic program costs such as personnel, management, and facilities maintenance. For expendable vehicles, it can include the cost of producing one vehicle, in order to keep production lines open.

Variable Recurring Cost is the extra cost associated with meeting different levels of demand. It will include, among other elements, the number of vehicles produced, transportation, assembly and payload integration, flight operations, and vehicle recovery (if necessary).

It should be noted that variable recurring cost in our model is not the “cost-per flight” as this value is commonly understood. Cost per flight is traditionally arrived at by adding the variable and fixed recurring costs, and dividing by the number of flights in a given year. The result is that cost-per-flight drops with increasing flight rate due both to a lower ratio of fixed-recurring-cost per flight, and economies of scale in production. For reusable vehicles such as the Space Shuttle, cost-per-flight drops sharply with increased flight-rate because reuse implies that variable recurring cost is lower than for expendable vehicles. Specific assumptions needed to arrive at these costs numbers are addressed in the section on modeling below.

Much can be understood about the sustainability of different programs simply understanding the relative size of these cost-segments. More specifically, the ratio of fixed-recurring to variable recurring cost has a large impact on long-term program costs. A program with low fixed recurring costs will be able to “weather” periods of low demand, without draining the Agency’s budget. Quite often, of course, this low fixed cost comes at the expense of higher variable recurring cost. If relatively high demand is guaranteed, the goal of maintaining a low fixed-recurring cost may be less important than keeping variable costs low.

Maintaining a low fixed recurring cost also has advantages in other ways. Most fixed-recurring costs go toward maintaining the workforce associated with the program, including basic facilities. A larger workforce creates strong political incentives and organizational inertia, which makes change the course of the program more difficult. Keeping the vehicle workforce as small as possible (and by extension, minimizing fixed recurring cost) thus both increase the flexibility of program costs in the face of change, and the flexibility of program direction, as the exploration vision evolves. This general discussion is of course directly transferable to the comparison of Shuttle-Derived and EELV derived systems, and will be elaborated upon in the discussion of model results.

4.0 Modeling Uncertainty in Demand

The Heavy Lift Vehicle must meet the ETO needs NASA’s exploration vision, while keeping costs as low as possible. Uncertainty in demand is thus a critical factor. This has two main elements: Schedule uncertainty and architectural uncertainty.

Schedule Uncertainty refers to the pattern of missions through time. When will the first lunar mission be launch, and how many will be launched thereafter? When will the first Mars mission be launch and how many thereafter? Depending on the level of fixed recurring costs, schedule uncertainty can greatly affect the life-cycle cost of a vehicle. Ideally, of course, an appropriate vehicle will be developed at a minimum time before it is needed. We can incorporate schedule uncertainty into the model by assuming 3 different schedule scenarios: low, medium, and high.

Architecture Uncertainty has to do with level of IMLEO per mission. Different Lunar and Mars architectures have been proposed, each with different IMLEO. This uncertainty can be modeled probabilistically.

Combining these two sources of uncertainty, we can create a notional decision-tree of the different factors that will affect the relative merits of each plan. The tree in Figure 2 is not exhaustive, but gives an idea of the different occurrences that could greatly affect future decisions. Moon 1, 2, 3 and Mars, 1, 2, 3 refer to three possible lunar and Mars architectures.

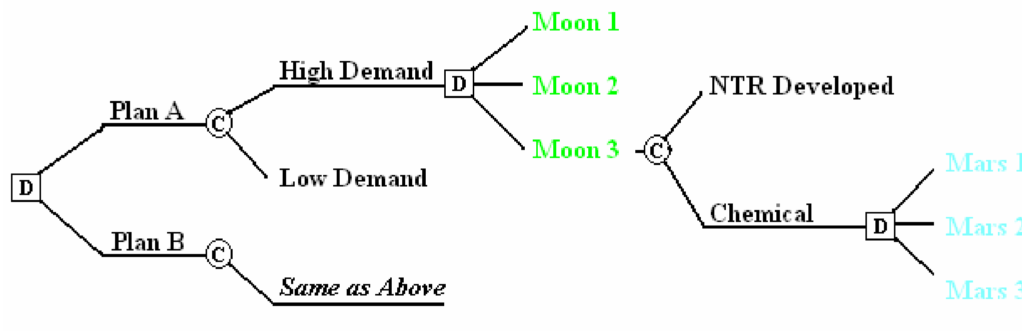

Figure 2: Notional Decision Tree View of Launch System Life-Cycle

The decision tree has both chance nodes and decision nodes. Chance nodes encompass factors that are beyond the control of system designers. Decision nodes are issues controlled by system designers. As illustrated, it is assumed that the heavy lift decision will be made before critical factors such as the level of demand and the exact lunar and Martian architectures have been established. This may not be the case. If the decision can be postponed, the optimal vehicle for lunar mission could be created, for example. Further, other factors such as the development of nuclear thermal rockets, may greatly affect these later decision points.

Of course, this tree is somewhat idealized. In reality, the various chance points may come before or after the decision points. The important fact is that all of this branch points are currently uncertain, and the relative advantages of different heavy-lift vehicles will change with them.

Also, exact probabilities are difficult to estimate. Our analysis overcomes this problem by examining sensitivities to changes in probabilities. Later analyses should consider using a probability density function for each decision and chance point.

A cost model can now estimate the total life-cycle costs for each plan along each path of the decision tree. By assigning probabilities to the various scenarios, with all of the scenarios totaling to a probability of one, we can estimate the expected cost along that path.

5.0 SDV vs EELV-Derived Architectures: Two Development Plans

Using these distinctions, we can create a discounted cash-flow model to evaluate the cost of different architectures under different demand scenarios. We can do this by creating two different development plans—one using EELV-derived vehicles and the other using SDVs—and comparing their total costs under different demand scenarios. These costs can be coupled to a decision tree representation of the Heavy-Lift decision, and assigned probabilities to calculate expected life-cycle cost.

The first step, then, is to limit the Heavy Lift architectural options for each development plan. Recent NASA studies suggest that a side-mount Shuttle-Derived system, with 4 or 5-segment SRBs is preferable to other configurations along multiple criteria [1]. The same NASA study also estimated costs for various elements of that program. Thus, let us define **Plan A** as follows: Develop a 4 or 5-segment side-mount shuttle derived system, beginning in 2010.

While the shuttle derived vehicles have lifting capacity of 82 and 95 metric tons to LEO, respectively, recent studies suggest that 40-60 metric vehicles should be adequate for lunar missions. This suggests that EELV-derived systems could be designed at this lower range, with the *option to expand to greater values for mars missions.* Thus, let us define **Plan B** as follows: Develop a 34 or 51 metric ton vehicle for lunar missions in 2010 and then develop a larger 100 metric vehicle for Mars-class missions. Figure 3 illustrates plan A and Plan B, using vehicles from the SDV study mentioned above and a recent ETO study conducted at NASA.

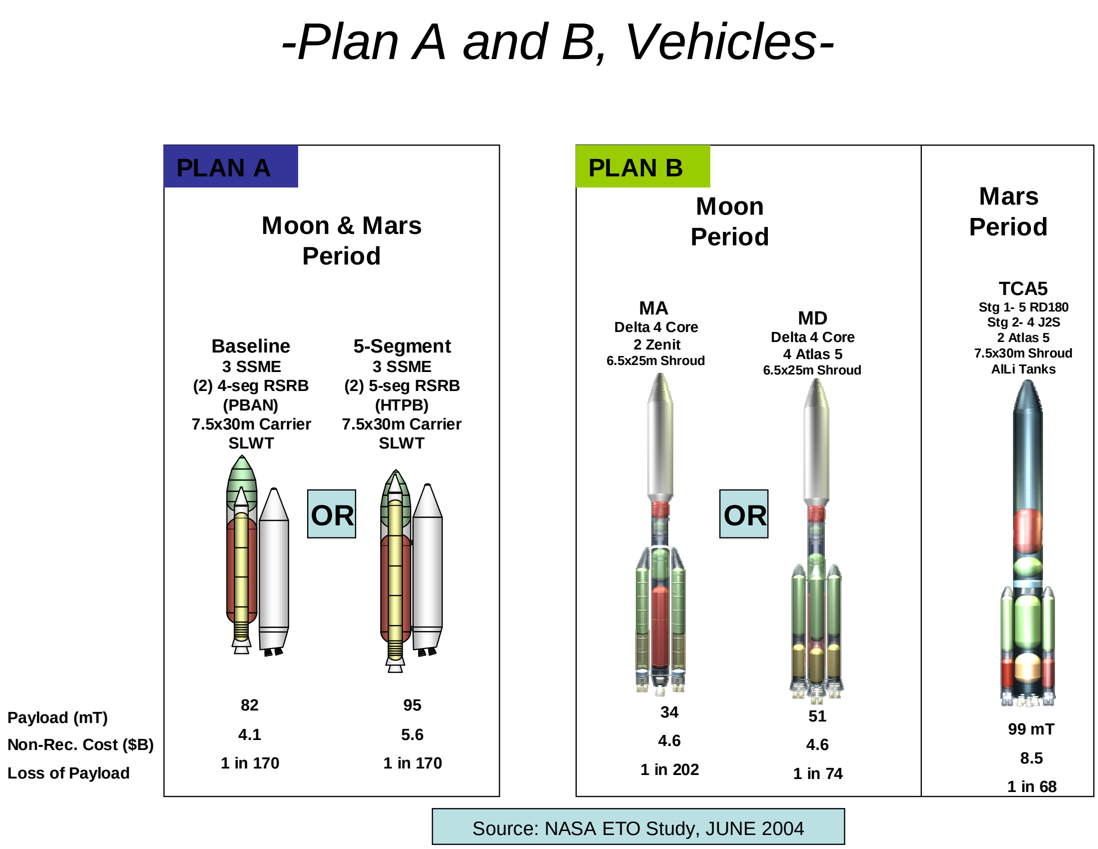

Figure 3: Two Plans for Heavy Lift Launch; SDV vs EELVD

As noted, the second plan constitutes an option to expand. In a traditional Real Options Analysis this plan could be compared to the same plan without the option to expand, thus determining the value of the options. Practically, however, the decision at NASA will involve developing plan A or B.

It is clear that both plans present different advantages. The SDV plans eliminate the need to develop two systems and make use of a lot of existing hardware. The EELV plans reduce fixed-recurring cost initially, by creating a smaller vehicle. They also give managers the discretion to begin building a larger system only when Mars travel is more certain, thus potentially freeing up more money for lunar travel now. The question remains how to estimate the three cost-elements described above for these systems, as a function of demand.

6.0 Shuttle-Derived Costs

As noted, the vehicle options for Plan A were taken from the "Exploration Transportation Team Task 5: Shuttle Derived Vehicles." Development costs and cost-per flight were estimated in this study for various SDV options. Cost numbers for our model were taken from this study as follows:

Development Cost: Taken from SDV study

Table 1: SDV Development Costs

	Total Dev Cost ($mil)
SDV 4Seg	$4,158
SDV 5Seg	$5,643

Variable Recurring: The SDV study had cost numbers for flight-rates of 1 through 4 per year for each SDV option. These followed a consistent pattern and were extrapolated for flight rates greater than 4.

Table 2: SDV 4-Segment Variable Recurring Costs

SDV 4 Segment Flights/yr	**1**	**2**	**3**	**4**
Program	$31	$47	$62	$76
Vehicle	$767	$1,275	$1,757	$2,226
Launch	$79	$81	$83	$85
Flight	$16	$16	$16	$17
Reserves	$111	$168	$220	$269
Total Cost	**$1,004**	**$1,588**	**$2,138**	**$2,673**

Table 3: SDV 5-Segment Variable Recurring Costs

SDV 5 Segment Flights/yr	**1**	**2**	**3**	**4**
Program	$32	$49	$64	$79
Vehicle	$786	$1,312	$1,813	$2,300
Launch	$93	$95	$97	$99
Flight	$16	$16	$16	$17
Reserves	$151	$248	$339	$428
Total Cost	**$1,077**	**$1,720**	**$2,330**	**$2,923**

Fixed Recurring: As noted, this is simply the cost of maintaining the launch-system if there are no-flights in that year. Theoretically it is the program cost (personnel, facilities, etc.) + the cost of producing one vehicle, ignoring the cost of launch and operations. Therefore, this cost includes the following from the tables above: 1 vehicle per year (to keep production lines open) + Program costs (personnel, etc). Launch, ops, and reserve cost not included.

Pre-Development Ramp-Up: In order to keep the possibility of developing a shuttle derived vehicle, certain long-lead-time purchases will need to be made very soon. It is not clear the exact costs of these purchases. We have therefore estimated a “ramp-up” of increasing funds through 2009, when development begins, and run the analysis with and without this ramp-up. The ramp-up is as follows:

Table 4: SDV “Ramp-Up”

Year	Cost ($million)
2006	200
2007	400
2008	600
2009	800
2010	1000

It should be noted that it was unclear how much this ramp-up would be, and how much of it should be billed to the SDV program, rather than the Shuttle Program. This question is beyond the control of the current analyses so, as stated, results were run with and without ramp-up.

7.0 EELV-Derived Costs

Vehicle options for Plan B were taken from a recent NASA study called: Vehicle options taken from: “ETO Trade Study for Future Moon-Mars Exploration,” Presented at NASA HQ, June 16, 2004. This study including development and recurring cost. However, because we want recurring cost as a function of demand, another value was needed.

We have already discussed in chapter 5 how the cost-per flight for large EELVs can be extrapolated from past cost. As with other capacity problems, economies of scale suggest that the relationship of size to average launch cost will follow a power law. We therefore have the following estimates for our cost elements:

Development Cost: Taken from ETO study, spread over 5 years and phased in same proportion as shuttle development cost:

Table 5: Development Cost Spread

Year	1	2	3	4	5
~ % Total Dev. Cost	7.5%	25%	35%	25%	7.5%

Table 6: EELVD Development Costs

	Dev. Cost ($mil)
34mt Delta IV Core and Zenit	$4,600
51mt Delta V Core 4 Atlas 5	$4,600
99mt TCA5	$8,500

Variable Recurring: Cost Per flight * Number of flights. Cost per flight is a function of capacity based on *power law* relationship using data from "International Guide to Launch Vehicles," by Isokawitz.[3] Only U.S. launchers included. No leaning curves assumed for increased production rates.

$$LaunchCost = 0.226 \times C^{0.66} \quad (\$\text{million})$$

Where C = Capacity in Kilograms

Fixed Recurring: The cost is modeled here as 89% of the cost of a single launch, based on a similar relationship between variable-recurring and fixed-recurring cost for Shuttle Derived Vehicles. (See next section)

8.0 The Discount Rate

The present value of a plan depends both on the amount of money spent, and when that money is spent. Discounting non-inflated costs takes into account the opportunity cost of investing sooner rather than later. If a plan enables us to push costs backward in time, for example, this has real value because we can use the money freed up now to move other priorities along (i.e. development of nuclear propulsion, etc).

More formally, we must note that the discount rate has two factors: interest and inflation. Interest represents the opportunity cost of investing now. If future costs are nominal--that is, in inflated dollars--they need to be reduced by both inflation and interest to get a one-to-one relationship with today's dollars. This is done using a "nominal discount rate." If future costs are "real" (that is, in constant-year dollars--as in our model), we only need to account for interest. This means we use the "real discount rate," which is the nominal rate minus inflation. These issues are explained in the OMB circular that sets forth the rates for government-project NPV analysis: http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html

There may be some debate as to how much "opportunity cost" should be counted in a NASA NPV analysis. Many studies appear to discount by inflation, or a "real" discount rate of 0. This means that future costs in constant-year dollars would not be discounted. This does not, however, provide for sound decision-making. Discounting at inflation ignores the benefits derived from having more discretion over future spending, including the very real benefit of being able to invest money now on other projects (such as nuclear thermal rockets). Thus, for the purpose of the heavy lift decision, it is most appropriate to use a "real discount rate" provided by the OMB circular. However, as this represents opportunity cost of investing it is difficult to estimate exactly and should be varied to determine sensitivity to discount.

9.0 Summary of the Model

Method of Analysis: Discounted cash flow models were created for four distinct development plans and computed under various demand scenarios. Major cost elements are: Development, Fixed-Recurring, Variable Recurring. The life-cycle costs for these pans were computed under three distinct demand scenarios: low, medium, and high.

Probabilities were assigned to the three plans, and *expected life-cycle costs calculated*. Pair-wise sensitivity analyses were run, as the probabilities between low-medium and medium-high varied between zero and one. The figure below illustrates the decision tree view of one of the medium to high pair-wise analysis.

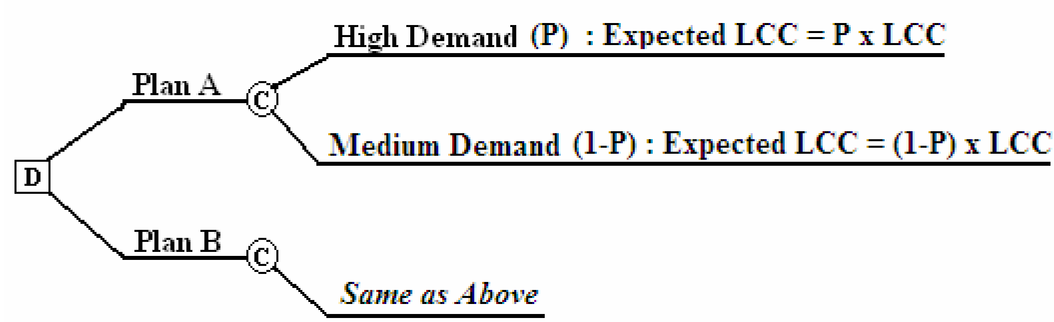

Figure 4: Decision Tree view of Expected-Cost Calculation

The Plans: Two basic vehicle architectures were evaluated, each with two iterations. All plans assume development begins in 2010. The plans are:

- **Plan A.1:** 4 Segment Side-Mount Shuttle-Derived launcher developed in 2010
- **Plan A.2:** 5 Segment Side-Mount Shuttle Derived Launch developed in 2010

- **Plan B.1:** 51 mt EELV-Derived launcher in 2010; Upgraded to 100mt for Mars Missions.
- **Plan B.2:** 34 mt EELVD launch begun in 2010; Upgraded to 100mt for Mars Missions.

Demand Scenarios: Launch Demand Scenarios were taken from the current MIT CE&R study estimates. They include low, medium, and high launch demand scenarios for a baseline Moon and to Mars architecture, each resulting in a set of IMLEOs each year until 2030. As noted, the architecture itself should also be varied probabilistically. This will be conducted in further analyses. Specifically, the demand scenarios are as follows. Year is at the top and the IMLEO is at the bottom.

Table 7: High Demand Scenario

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CTS	Cargo	Habitat	Cargo	Mars PD	CTS	Mars PD	Cargo	Mars PD	CTS	Mars PD	Cargo	Mars PD	CTS	Mars PD
		CTS	CTS			Crew	CTS	Crew		Crew	CTS	Crew		Crew

127	**100**	**344**	**227**	**403**	**127**	**673**	**227**	**673**	**127**	**673**	**227**	**673**	**127**	**673**

Table 8: Medium Demand Scenario

2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
CTS	Cargo	Habitat	Cargo	Mars PD		Mars PD		Mars PD		Mars PD		Mars PD		Mars PD
		CTS	CTS			Crew		Crew		Crew		Crew		Crew
127	**100**	**344**	**227**	**403**		**673**		**673**		**673**		**673**		**673**

Table 9: Low Demand Scenario

2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	CTS		Cargo	Habitat		Cargo		Mars PD		Mars PD		Mars PD		Mars PD
				CTS		CTS				Crew		Crew		Crew
	127		**100**	**344**		**227**		**403**		**673**		**673**		**673**

10.0 Results

Life cycle costs were calculated with and without the ramp-up costs for the Shuttle Derived program. Figure 5 illustrates total discounted life-cycle costs for the four plans, with shuttle ramp-up costs included. Two facts are most striking: First, both Shuttle Derived plans are more expensive than EELV-derived plans across all scenarios. Second, the relative benefit of EELV derived vehicles increases as demand increases. Factors affecting this comparison are addressed below.

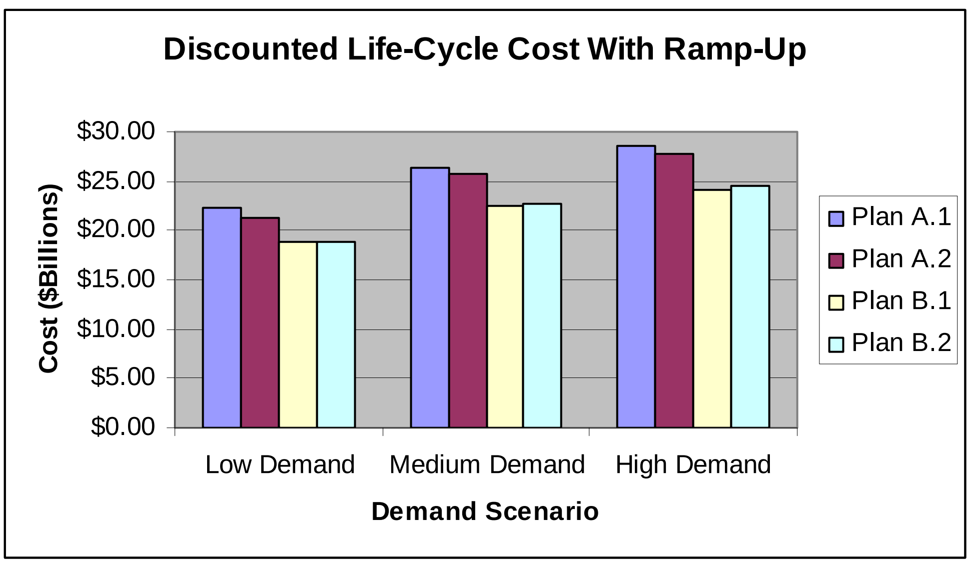

Figure 5: Discounted Life-Cycle Cost Comparison, With Shuttle Ramp-Up Costs. 3.5% Discount Rate.

Figure 6 presents discounted life-cycle cost of the four plans without shuttle ramp-up costs. Here, the Shuttle-Derived plan with 5-segment SRBs is better than all other plans at low demand. At higher demand, EELV-derived vehicles again beat SDVs. It is important to note that the lack of ramp-up costs removes approximately $3 billion dollars in development-related costs. The exact cost of the ramp-up must be known with more precision if a sound decision is to be made.

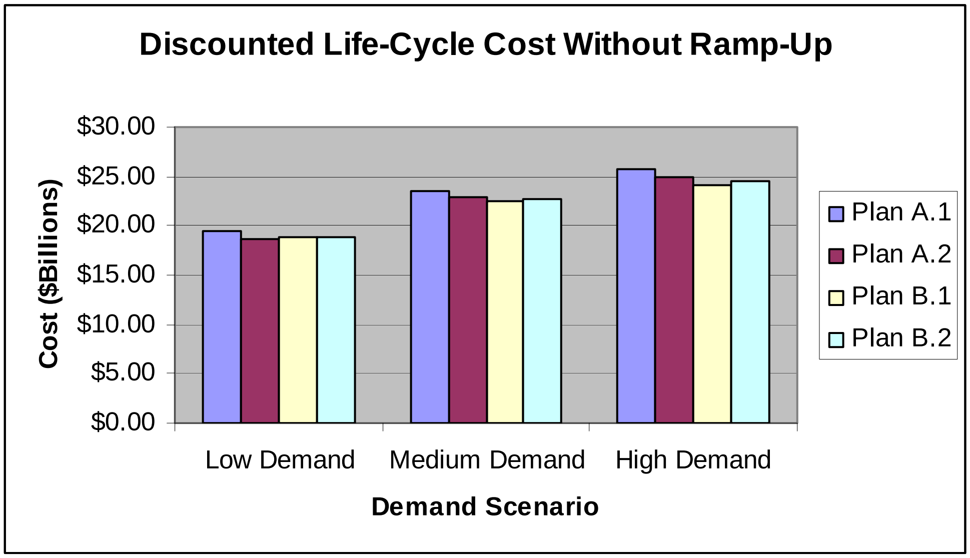

Figure 6: Discounted Life-Cycle Cost Comparison, Without Shuttle Ramp-Up Costs. 3.5% Discount Rate.

Probabilistic Analysis: The only cross-over point in this analysis thus exists between low and medium or low and high demand, with shuttle ramp-up costs *not* included. A decision-tree approach can be used to calculate expected life-cycle costs as a function of the probability that one of these demand scenarios will occur. To do this we need a probability density function (PDF). We can estimate the PDF as uniform, although in reality it will probably be skewed. Future analyses will include a different non-uniform PDFs. It must be noted, however, that a uniform PDF creates a linear relationship between probability of demand scenario and cost. The result is a linear extrapolation from high to low-demand life-cycle costs.

Figure 7 illustrates the expected life-cycle cost of a the four plans, as a function of the probability that a low versus high demand scenario will occur. It demonstrates that when there is approximately *15% chance of high demand or greater*, EELV-derived plans are superior to the Shuttle-Derived Plan A.2.

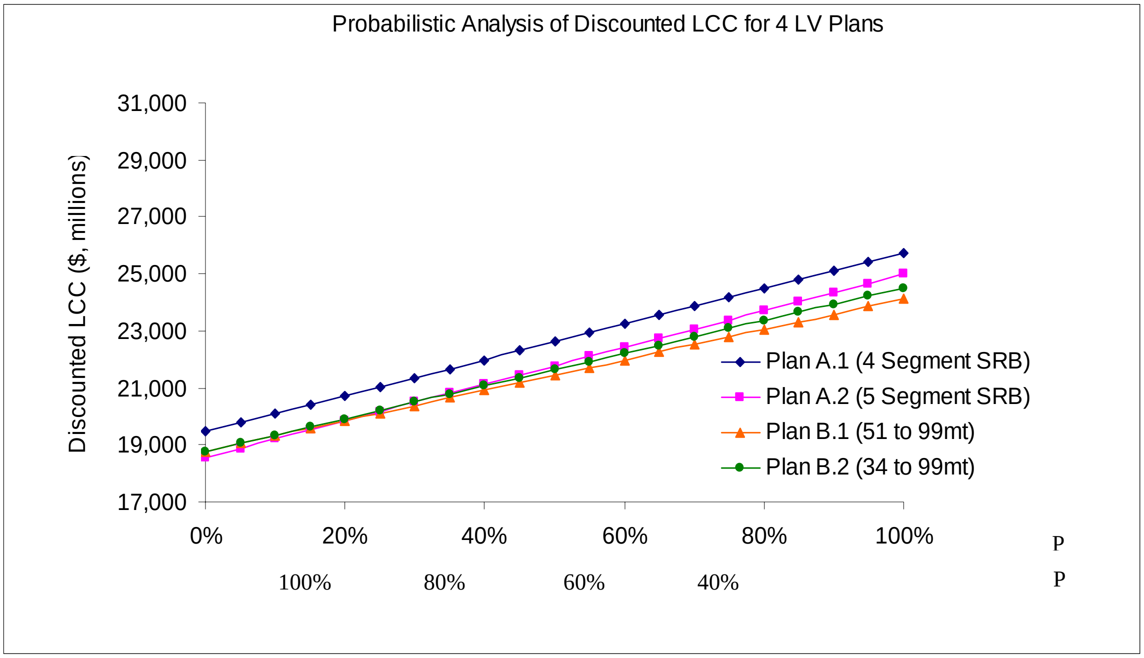

Figure 7: Model Results without ramp-up; 3.5% discount rate; Low to High Demand.

11.0 Conclusion

According to our assumptions, if the ramp-up is included, the Shuttle-Derived programs are clearly more expensive over their life-cycle than EELV-derived systems. If an SDV ramp-up is not included, SDV vehicles are more cost-effective the EELVD under lower-demand scenarios, however, EELVD are still less costly that SDV at medium and high demand levels. The cross-over point here is approximately 85% chance or greater that a low demand scenario will occur.

Various factors influence these outcomes. Smaller launchers benefit over a wider range of scenarios because fixed recurring costs are lower, so total costs follow demand more exactly than for shuttle-derived vehicles. SDV plans benefit because they require only one development effort, while EELVD plans required a development effort prior to both lunar and mars missions. However, the single development effort of the SDV comes at the expense of higher fixed recurring and variable recurring costs. An SDV vehicle is likely larger than needed for lunar missions, and this means that a larger vehicle is built and maintained sooner. Also, it is relatively safe to say that an 80+mt SDV would be built purely for NASA missions, while an EELVD may be created around a core of vehicles and expertise which transfers to the commercial and military domain. This may relax the fixed recurring costs (in the form of personnel and facilities) for NASA when demand is low.

Sensitivity The immediate question arises as to how sensitive the results are to changes in assumptions. Sensitivity analysis has been conduct on a first version of this model. These analyses suggest that final results are less sensitive to changes in architecture (that is, changes in IMLEO for each mission) and changes in discount rate, than they are to changes in the schedule of demand.[4] Sensitivity to changes in demand, however, increases with discount rate. Therefore, it may be prudent to establish which discount rate will be used when making the decision. Sensitivity to IMLEO using updated lunar and mars architectures is currently being included in a third version of the model.

Options on EELV: It must be noted that, although all cost number are uncertain, a critical category of EELV costs were likely over-estimated. Plan B.1 or B.2 were designed as initial systems with options to expand, however, the development cost of the expansion was modeled as an independent development effort. Options to expand that would be built into EELV-derived systems, however, would lower the cost of this second effort. These might include modifying launch facilities to accommodate a Mars-Class launch when pad mods for the smaller launch were conducted. Also, designing a launcher with the ability to accommodate an additional stage or large additional boosters may. These possibilities should be examined in more detail.

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[1] "Exploration Transportation Team Task 5: Shuttle Derived Vehicles." Presented by Steve Davis. NASA HQ. Spring 2004

[2] De Neufville, Richard. "Systems Analysis for Design." Class Notes, 2003
Shuttle Derived Vehicles Report, Spring 2004

[3] Isakowitz, Steven J. "International Reference Guide to Space Launch Systems, Fourth Edition." AIAA, © 2004, 4th Edition. ISBN: 156347591X

[4] This is based on work done at NASA HQ in the summer of 2004, for which a presentation was made to the NASA Space Architecture Office.